A 34.5 GHz 200 kW CW TM_{11}-HE_{11} Mode Converter for Gyrotron Applications

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1 Introduction

Future plans call for increasing the uplink and downlink frequencies used for communication with deep space probes from the present 2 GHz and S GHz bands into the millimeter band, 32-35 GHz. High power transmitters, on the order of several hundred kilowatts CW will thus be required in the millimeter band. The only sources presently capable of producing this power level are gyro devices. In order to produce these power levels gyro devices employ unconventional interaction cavities. These cavities resonate in higher order waveguide modes, and typically deliver the output signal into an oversize circular waveguide in a higher order waveguide mode, such as a TE_{0N} mode. If the power is to be used constructively, for example to illuminate a reflector antenna, a Gaussian beam is typically required. Transformation of the TE_{0N} mode into a Gaussian beam is achieved through the use of several mode converters. One possible system of mode converters is depicted in Figure 1. Here the TE_{01} mode is emitted by the gyrotron into highly overmoded circular waveguide. The TE_{01} mode then enters the TE_{01}-TM_{11} mode converter, which consists of circular waveguide bend. The TM_{11} mode then enters a corrugated TM_{11}-HE_{11} mode converter, and finally exits into space through a corrugated horn section. The next section will describe the mode converters used to generate the TM_{11} mode required for testing the TM_{11}-HE_{11} mode converter. It will be followed by details of the TM_{11}-HE_{11} mode converter itself.

II TE_{01} - TM_{11} Mode Conversion

For the application at hand the gyrotron oscillator is assumed to emit a TE_{01} waveguide mode in 1 inch diameter circular waveguide at 34.3 GHz. For test purposes the TE_{01} mode is generated using a an Alpha TRG model 330A TE_{01} Mode Transition, Mode Filter, and taper. The TE_{01} mode was then in turn passed through a 51.5 degree bend. The TE_{01} and TM_{11} modes have identical propagation coefficients, and are tightly coupled through the curvature perturbation. Analysis of the TE_{01}-TM_{11} mode converting bend is carried out using coupled mode theory, as described in [1,2]. Rather than using a constant radius bend as in [1], a sinusoidal curvature distribution was employed. This eliminates the discontinuity in curvature when the bend is terminated in straight waveguides at each end, reducing the amplitudes of the spurious modes. Figure 2 plots the major modes excited along the bend, which was chosen to have an overall arc length of 20 inches. The amplitudes of the two main modes and several of the spurious modes which are coupled in the bend are included. Including losses the conversion efficiency of the bend is computed to be 99.8 per cent. The bend was fabricated in two halves using a numerically controlled mill and bolted together. The efficiency of the conversion process was confirmed experimentally by measuring the radiation pattern at the output of the bend. Results of the far field measurement are shown in Figure 3, where the co polarized radiation, (electric field perpendicular to the plane of

curvature), is plotted. The dual lobed pattern of the TM_{11} mode is clearly visible, and the excellent pattern symmetry indicates a low content of spurious modes. This component was then used to generate a highly pure TM_{11} mode in overmoded circular waveguide for testing the TM_{11}-HE_{11} mode converter and horn assembly.

11 TM_{11} HE_{11} Mode Conversion

As Figure 3 illustrates, the radiation pattern of the TM_{11} is not suitable for illuminating a reflector antenna. Instead a pencil beam, or Gaussian beam, is required. The hybrid HE_{11} mode in corrugated waveguide is widely used as an efficient illuminator for reflector antennas. In more conventional applications a TE_{11} circular waveguide mode is generated from the standard rectangular waveguide mode through a simple single mode rectangular to circular waveguide transition. The TE_{11} mode is then transformed into the HE_{11} mode using a corrugated circular waveguide section where the corrugation depth is gradually decreased from one half wavelength (λ/2) to one quarter wavelength (λ/4). [3].

Conversion of the TM_{11} mode into the HE_{11} mode may also be accomplished through the use of a corrugated waveguide section. [1]. In this case the corrugation must be increased from zero depth to one quarter wavelength along the converter. Since a large number of modes may propagate in the 1 inch diameter waveguide at 31.3 GHz, care must be taken in the design of the converter in order to eliminate the excitation of spurious modes. The level of excitation of the spurious modes may be minimized by changing the groove depth gradually, i.e. increasing the length of the converter. Spurious mode conversion may also be minimized by adjusting the groove depth versus longitudinal distance profile. One possibility is to choose a profile based upon coupled wave theory which minimizes coupling to the nearest spurious mode, [1].

For the design of the present converter a more rigorous analysis method than coupled mode theory was employed. A mode matching technique has been used to compute the performance of the converter, [3]. Using this analysis method interactions between all of the higher order waveguide modes, including reflected modes, is automatically taken into account. This analysis method has been used in conjunction with an empirical method for determining the corrugation depth profile. A number of linear segments were used to model the profile. The number of segments and their slopes were then optimized using radiation pattern symmetry, minimum reflected power, and minimum converter length as criteria. The final design consists of a two segment profile for the groove depth in the converter section. The grooves increase from zero depth to 0.04 inches over a length of 5.92 inches, and then from 0.04 inches to 0.08 inches over an additional length of 2.96 inches, resulting in a total converter length 8.88 inches. In this way the groove depth changes most gradually near the shallow groove depths, where the coupling to spurious modes is highest. In particular, coupling to the EH_{12} surface wave mode can be significant for shallow groove depths. Coupling to this mode degrades the radiation pattern and increases the reflected power significantly. Using two thirds of the overall converter length to reach half of the required corrugation depth, and an overall converter length to 8.88 inches was found to be sufficient to produce a high quality beam and low reflected power. For the present application the gain associated with a 1 inch diameter aperture is insufficient, and therefore the converter is followed by a linear horn section of length 5.88 inches where the aperture diameter is increased to 2 inches.

Figure 4 plots the converted mode content along the converter and horn section as a function of distance. As can be seen in the figure initially all of the power is in the TM_{11} mode, and it is gradually transferred into the TE_{11} mode along the converter. At the end of the converter, 8.88 inches, a stable configuration is reached, with approximately 20 percent of the input power remaining in the TM_{11} mode, and 80 percent in the TE_{11} mode. This ratio
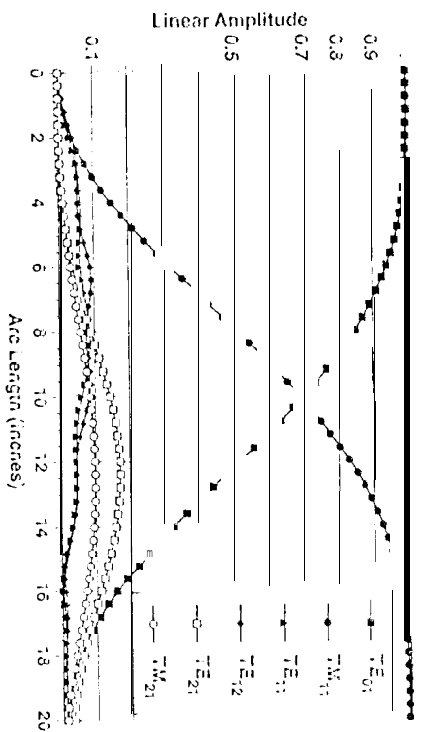
Linear Amplitude

Arc Length (inches)

TE₀₁ — TE_{01}
TM₁₁ — TM_{11}
TE₁₁ — TE_{11}
TE₁₂ — TE_{12}
TE₂₁ — TE_{21}
TM₁₁ / TM₂₁ — TM_{11}/TM_{21}

Figure 2. Mode Content in $TE_{01} \rightarrow TM_{11}$ Converter

Linear Magnitude

$TM_{11}^{(T)}$

$TE_{11}^{(T)}$

Converter Section

Horn Section

$TE_{11}^{(r)}$

Position (inches)

Figure 4. Mode Content in $TM_{11} \rightarrow TE_{11}$ Converter

Amplitude(dB)

Azimuth(Deg)

Elevation(Deg)
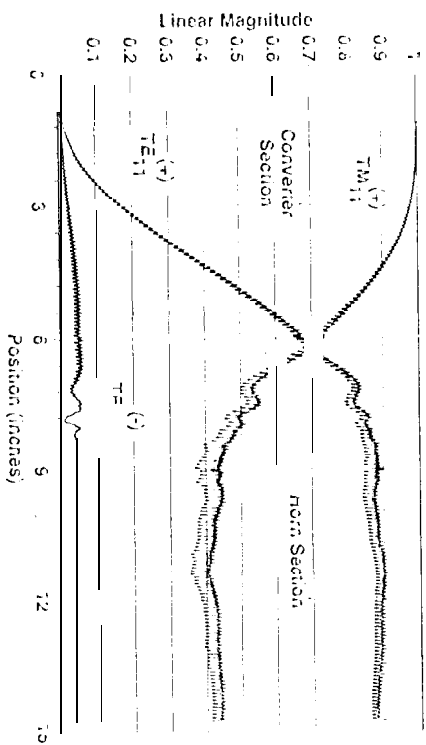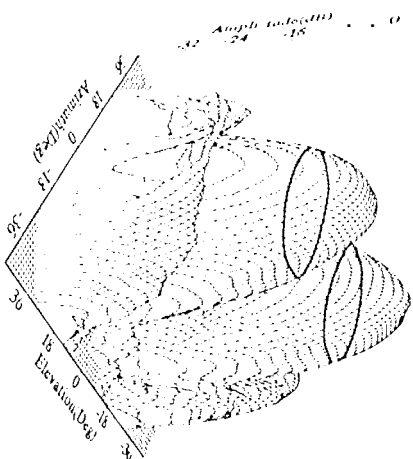
Fig. 3.3. Measured TM_{11} Radiation Pattern

Amplitude(dB)

Azimuth(Deg)
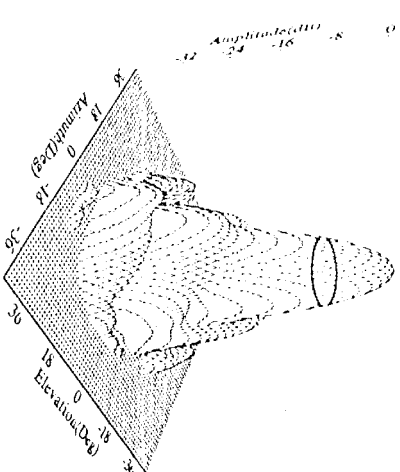
Elevation(Deg)

Figure 5. Measured TE_{11} Radiation Pattern

produces the desirable characteristics of the HE_{11} mode, equal beamwidth in the E and H planes, and low cross polarization. As figure 4 shows, once this ratio is established it propagates essentially unaffected through the horn section where the corrugation depth remains constant. The ripple on the mode content curves is associated with the redistribution of power as the wave passes from groove sections to land sections in the corrugated converter and horn. As can be seen in the plot, reflections build up in the converter section to a level of about 0.04, or a return loss of 28 dB. This level is acceptable for the present application, but may be reduced through the use of a longer mode converter section. The final radiation pattern measured at the output of the TE_{01}-TM_{11} mode converter-TM_{11} - HE_{11} mode converter/horn combination is plotted in Figure 5. As expected, a highly symmetric pencil beam with low sidelobes is generated. The slight asymmetry in the measured pattern is due to low levels of spurious mode power generated in the TE_{01}-TM_{11} mode converter. Comparison of Figures 3 and 5 illustrates the ability of the converter to transform the dual lobed radiation pattern of the TM_{11} mode into the highly desirable pattern of the HE_{11} mode.

References

[1] J. L. Doane, "Mode Converters for Generating the HE_{11} (Gaussian-Like) Mode from TE_{01} in Circular Waveguide", International Journal of Electronics, Vol. 53, pp. 573-584, 1982.

[2] J. L. Doane, "Propagation and Mode Coupling in Corrugated and Smooth-Wall Circular Waveguides", Infrared and Millimeter Waves, Vol. 13, Part IV, pp.123-170, Ed. K. J. Button

[3] G. L. James, "Analysis and Design of TE_{11}-to HE_{11} Corrugated Cylindrical Waveguide Mode Converters", IEEE Transactions on Microwave Theory and Techniques, MTT-29, NO. 10, pp. 1059-1066, Oct. 1981.

GYROTRON: 34.3 GHz
200 KW CW, TE 01 MODE
OUTPUT

TE 01 - TM 11 MODE
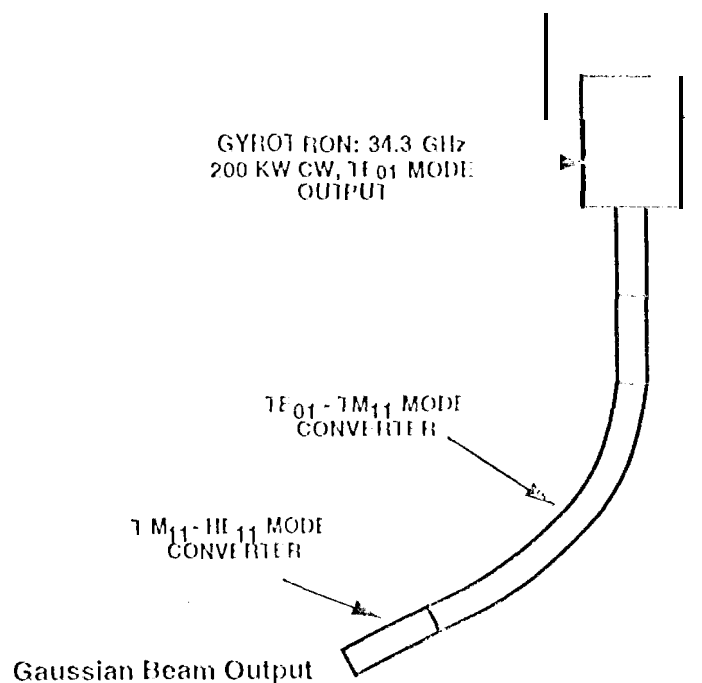CONVERTER

TM 11 - HE 11 MODE
CONVERTER

Gaussian Beam Output

Figure 1. Gyrotron Oscillator and Mode Converters